Gone Fission: A Guide to Evaluating Risks Due to High-Z Materials in Active EEE Parts

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Acronyms

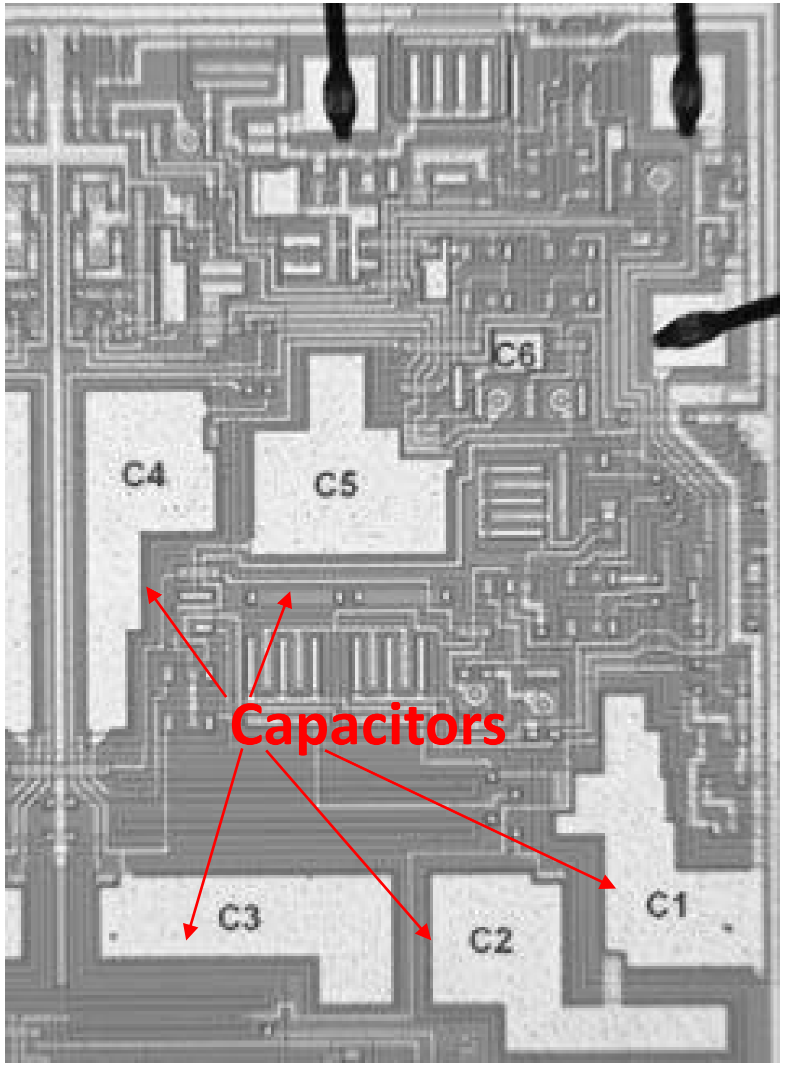
- Analog Devices (ADI)
- Destructive SEE (DSEE)
- Electronics and Electrical Engineering (EEE)
- Leadless Chip Carrier (LCC)
- linear energy transfer (MeV•cm^2/mg) (LET)
- equivalent linear energy transfer (LET_{EQ})
- millibarn, 1 barn = 10^{-24} cm^2 (mbarn)
- multi-bit upset (MBU)
- operational amplifier (op amp)
- single event burnout (SEB)
- single event dielectric rupture (SEDR)
- single event effect (SEE)
- single event functional interrupt (SEFI)
- single event gate rupture (SEGR)
- single event latchup (SEL)
- sensitive volume (SV)
- worst-case (WC)

Summary of the Failures

- In 200-MeV proton test, Dan Clymer of Lockheed-Martin saw unexpected failures in an Analog Devices (ADI) OP470 op amp
- Capacitors in OP470 known to fail due to heavy ion SEE, but:
  - Required ions w/ LET>20 MeVcm^2/mg, while proton-Si collisions produce LET<14 MeVcm^2/mg
- And it gets weirder
  - Failures only seen with parts in Leadless Chip Carrier (LCC) package
  - If lid of LCC package removed, no failures seen
- A clue: LCC lids had gold plating on the underside (facing die)

- Tests on other devices showed gold lid was the integral to the failure mode.
- Note that most cross sections <<10^{-11} cm^2.
- List not exhaustive.

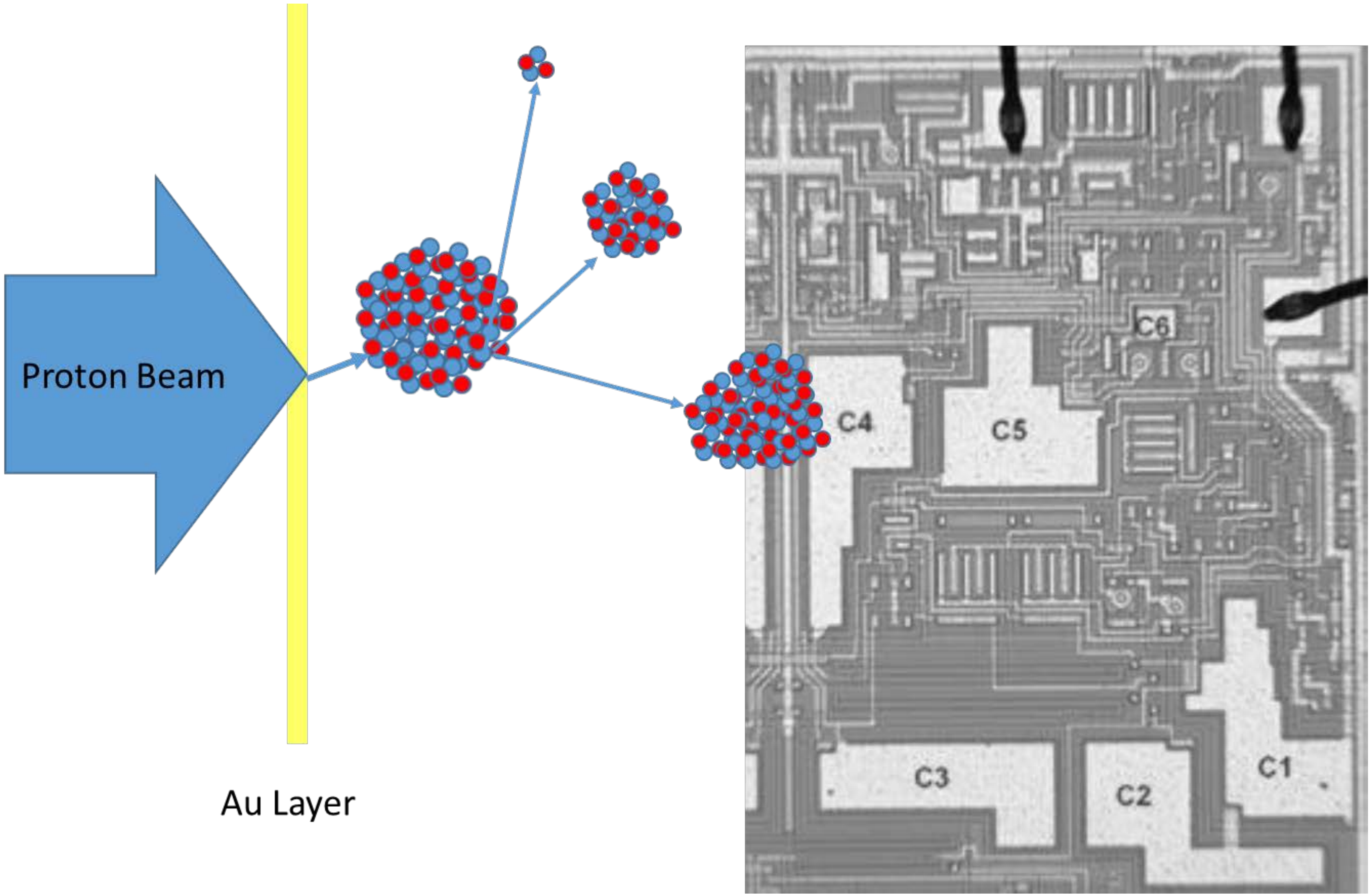
Part	Package	Tested	C. Section	Voltage
AD667	LCC FP	2	None	N/A
AMP01	LCC	11	2.70E-12	±15.0
OP12	Custom	2	3.50E-12	±18.0
OP27	Custom	2	4.20E-12	±17.0
OP200	LCC	2	1.80E-12	±15.0
OP400	LCC	1	2.00E-12	±18.0
OP470	Multiple	106	4.90E-12	±14.0
OP471	Custom	1	6.10E-11	±17.0



Quadrant of ADI OP470 quad op amp

Adapted from T. Turflinger et al., IEEE Trans. On Nuclear Science, Vol. 62, no. 6,p. 2468.

Failure Mechanism



- Proton beam knocks Au nucleus out of Au layer
- Excited Au nucleus oscillates then fissions into two nuclei ($30<Z<50$)
- Fission fragment strikes capacitor, depositing enough charge to rupture capacitor oxide (<100 nm)
- Failure more likely if ion incident normally to device surface
- Almost all energy of fission ions comes from fission
- Ions have short range.

Daughter Product Yields vs. Z and E

E \ Z	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
43.6	0.E+00	0.E+00	0.E+00	0.E+00	8.E-09	0.E+00	8.E-09	2.E-08	6.E-08	9.E-08	2.E-07	4.E-07	4.E-07	7.E-07	9.E-07	1.E-06	1.E-06	2.E-06	2.E-06	2.E-06	2.E-06	2.E-06
45.5	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	8.E-09	3.E-08	6.E-08	1.E-07	2.E-07	3.E-07	6.E-07	8.E-07	1.E-06	1.E-06	2.E-06	2.E-06	3.E-06	2.E-06	3.E-06	2.E-06	2.E-06
47.5	0.E+00	0.E+00	0.E+00	2.E-08	2.E-08	3.E-08	5.E-08	2.E-07	2.E-07	4.E-07	6.E-07	1.E-06	1.E-06	2.E-06	2.E-06	3.E-06	3.E-06	3.E-06	3.E-06	3.E-06	2.E-06	2.E-06
49.4	0.E+00	0.E+00	0.E+00	8.E-09	0.E+00	4.E-08	1.E-07	3.E-07	4.E-07	7.E-07	9.E-07	2.E-06	2.E-06	3.E-06	3.E-06	4.E-06	5.E-06	5.E-06	4.E-06	4.E-06	2.E-06	2.E-06
51.3	0.E+00	8.E-09	0.E+00	3.E-08	4.E-08	1.E-07	2.E-07	4.E-07	6.E-07	1.E-06	2.E-06	3.E-06	3.E-06	5.E-06	5.E-06	5.E-06	6.E-06	5.E-06	4.E-06	4.E-06	3.E-06	2.E-06
53.3	8.E-09	2.E-08	3.E-08	8.E-08	1.E-07	2.E-07	4.E-07	6.E-07	1.E-06	2.E-06	3.E-06	4.E-06	4.E-06	6.E-06	6.E-06	7.E-06	7.E-06	6.E-06	5.E-06	4.E-06	2.E-06	2.E-06
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57.1	2.E-08	2.E-08	7.E-08	2.E-07	3.E-07	6.E-07	1.E-06	2.E-06	3.E-06	4.E-06	5.E-06	7.E-06	7.E-06	9.E-06	8.E-06	8.E-06	8.E-06	6.E-06	4.E-06	4.E-06	2.E-06	1.E-06
59.1	6.E-08	1.E-07	2.E-07	2.E-07	6.E-07	8.E-07	2.E-06	2.E-06	4.E-06	5.E-06	6.E-06	9.E-06	9.E-06	1.E-05	9.E-06	9.E-06	8.E-06	6.E-06	4.E-06	3.E-06	2.E-06	9.E-07
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62.9	7.E-08	2.E-07	4.E-07	6.E-07	1.E-06	2.E-06	3.E-06	5.E-06	6.E-06	8.E-06	9.E-06	1.E-05	1.E-05	1.E-05	9.E-06	8.E-06	7.E-06	5.E-06	3.E-06	2.E-06	1.E-06	5.E-07
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66.8	3.E-07	5.E-07	8.E-07	1.E-06	2.E-06	3.E-06	5.E-06	7.E-06	9.E-06	1.E-05	1.E-05	1.E-05	1.E-05	1.E-05	8.E-06	7.E-06	5.E-06	3.E-06	2.E-06	1.E-06	5.E-07	3.E-07
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70.6	4.E-07	8.E-07	1.E-06	2.E-06	3.E-06	5.E-06	7.E-06	8.E-06	1.E-05	1.E-05	1.E-05	1.E-05	9.E-06	8.E-06	6.E-06	4.E-06	3.E-06	2.E-06	9.E-07	5.E-07	2.E-07	8.E-08
72.6	5.E-07	8.E-07	2.E-06	3.E-06	4.E-06	5.E-06	7.E-06	9.E-06	1.E-05	1.E-05	1.E-05	1.E-05	7.E-06	6.E-06	4.E-06	3.E-06	2.E-06	1.E-06	5.E-07	2.E-07	2.E-07	3.E-08
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78.4	1.E-06	2.E-06	3.E-06	4.E-06	5.E-06	6.E-06	7.E-06	8.E-06	8.E-06	8.E-06	6.E-06	5.E-06	4.E-06	3.E-06	2.E-06	1.E-06	5.E-07	2.E-07	9.E-08	3.E-08	8.E-09	0.E+00
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82.2	1.E-06	2.E-06	2.E-06	4.E-06	5.E-06	5.E-06	6.E-06	6.E-06	6.E-06	5.E-06	4.E-06	3.E-06	2.E-06	1.E-06	6.E-07	2.E-07	2.E-07	6.E-08	3.E-08	0.E+00	0.E+00	0.E+00
84.2	1.E-06	2.E-06	2.E-06	3.E-06	4.E-06	5.E-06	5.E-06	5.E-06	5.E-06	4.E-06	2.E-06	2.E-06	1.E-06	7.E-07	4.E-07	2.E-07	2.E-08	2.E-08	8.E-09	8.E-09	8.E-09	0.E+00
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90.0	1.E-06	1.E-06	2.E-06	2.E-06	3.E-06	2.E-06	2.E-06	2.E-06	2.E-06	1.E-06	6.E-07	5.E-07	3.E-07	1.E-07	3.E-08	3.E-08	2.E-08	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00
91.9	9.E-07	1.E-06	2.E-06	2.E-06	2.E-06	2.E-06	2.E-06	2.E-06	1.E-06	8.E-07	3.E-07	2.E-07	1.E-07	5.E-08	3.E-08	2.E-08	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00

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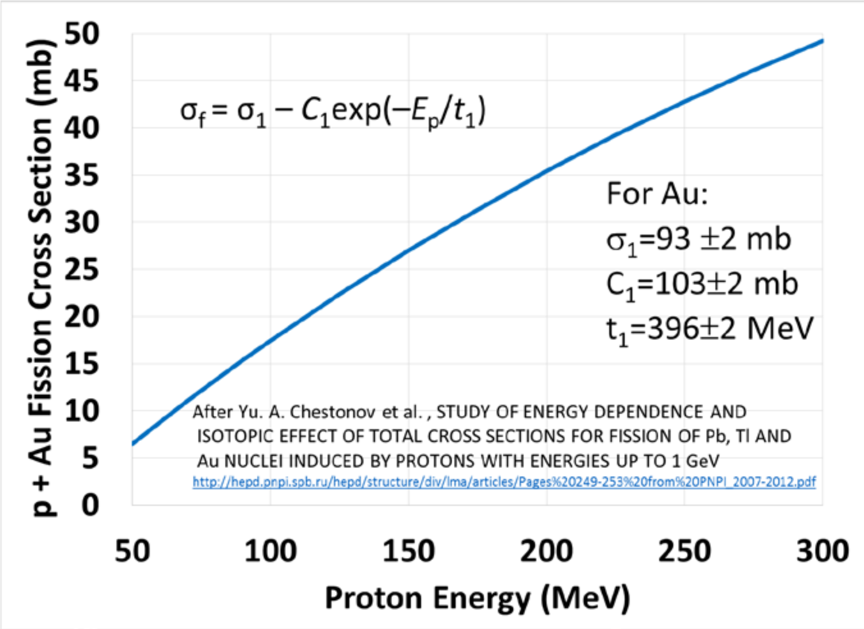
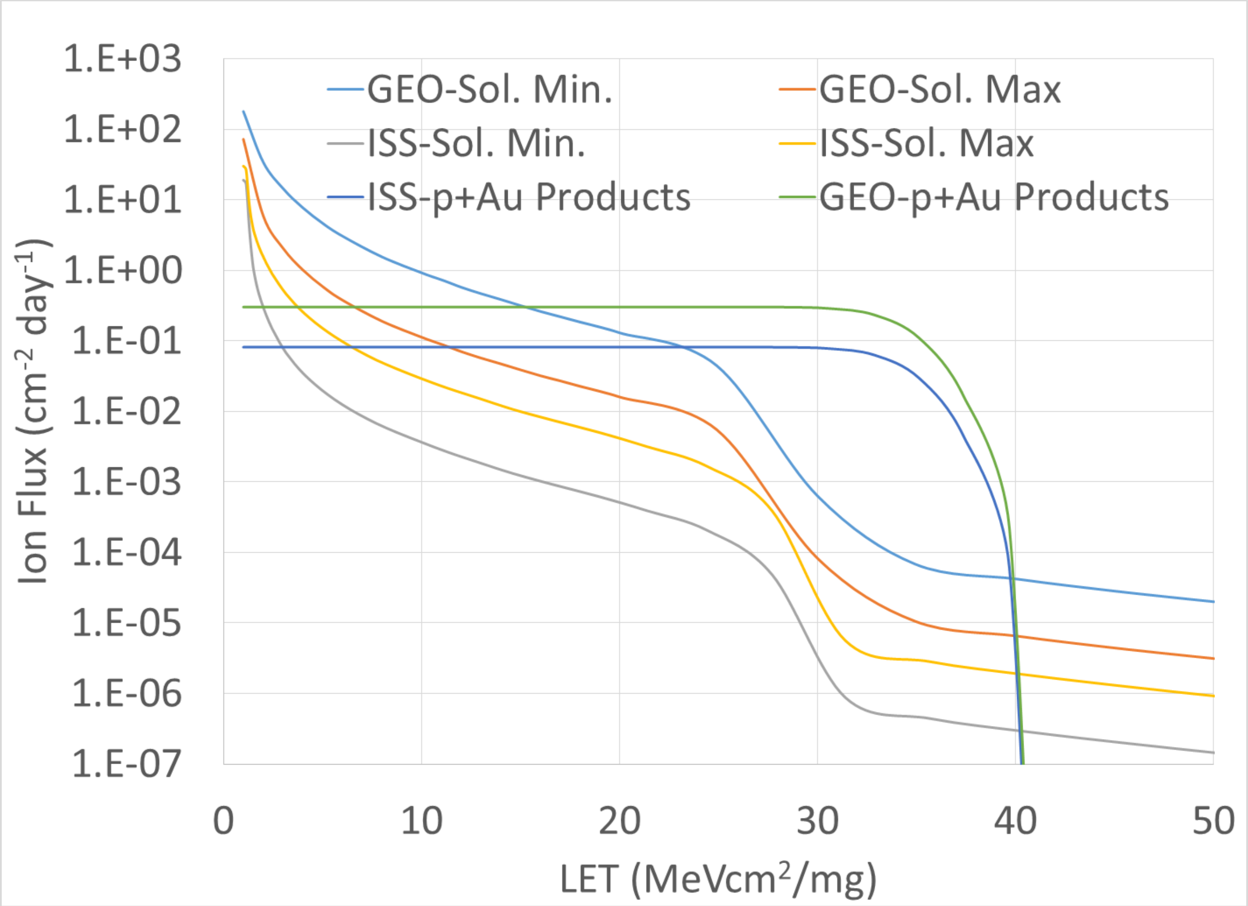
First the Bad News…Then The Good

- Cross section per Au nucleon~35 mbarn, or 3.5E-26 cm^2 @ 200 MeV
  - Varies from 6.5 mb at 50 MeV to about 49 mb @ 300 MeV
- 1 cm^2 of 1-um thick Au foil has ~5.9E18 Au nuclei
- 1E10 200-MeV protons/cm2→2100 Au fissions
- Daughter products have 30<LET<40 $MeVcm^2/mg$

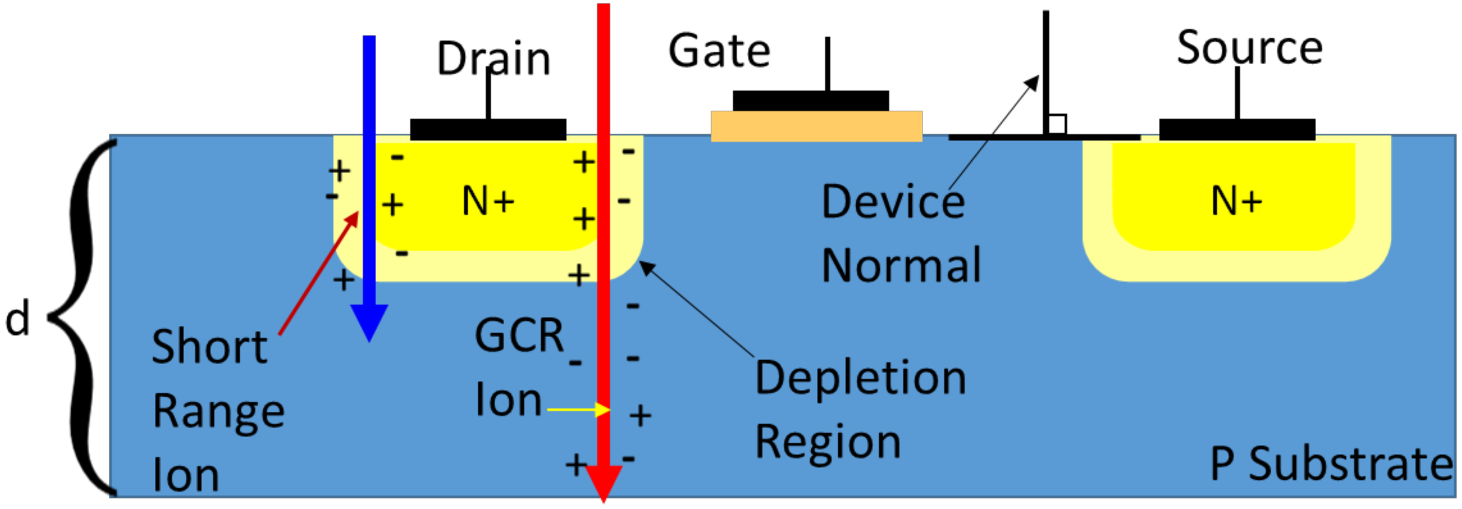




Although high LET, daughter products are short range (<17 μm)

SEE Cross Section Scales w/ Deposited Charge, Not LET

- Given LET and flux ranges, main concern is destructive SEE (DSEE)
  - Most DSEE have deep sensitive volumes
  - Depth, d~10s of microns
- SEE cross section scales w/ deposited energy E_{dep}, not LET
- For most DSEE, energy E_{dep} for fission product limited by ion range, not LET
- GCR, SPE and most accelerator ions traverse entire SV w/ ~constant LET
- Risk limits based on short ion range
  - Range << SV depth
  - Finite propagation length in Au and overburden above SV



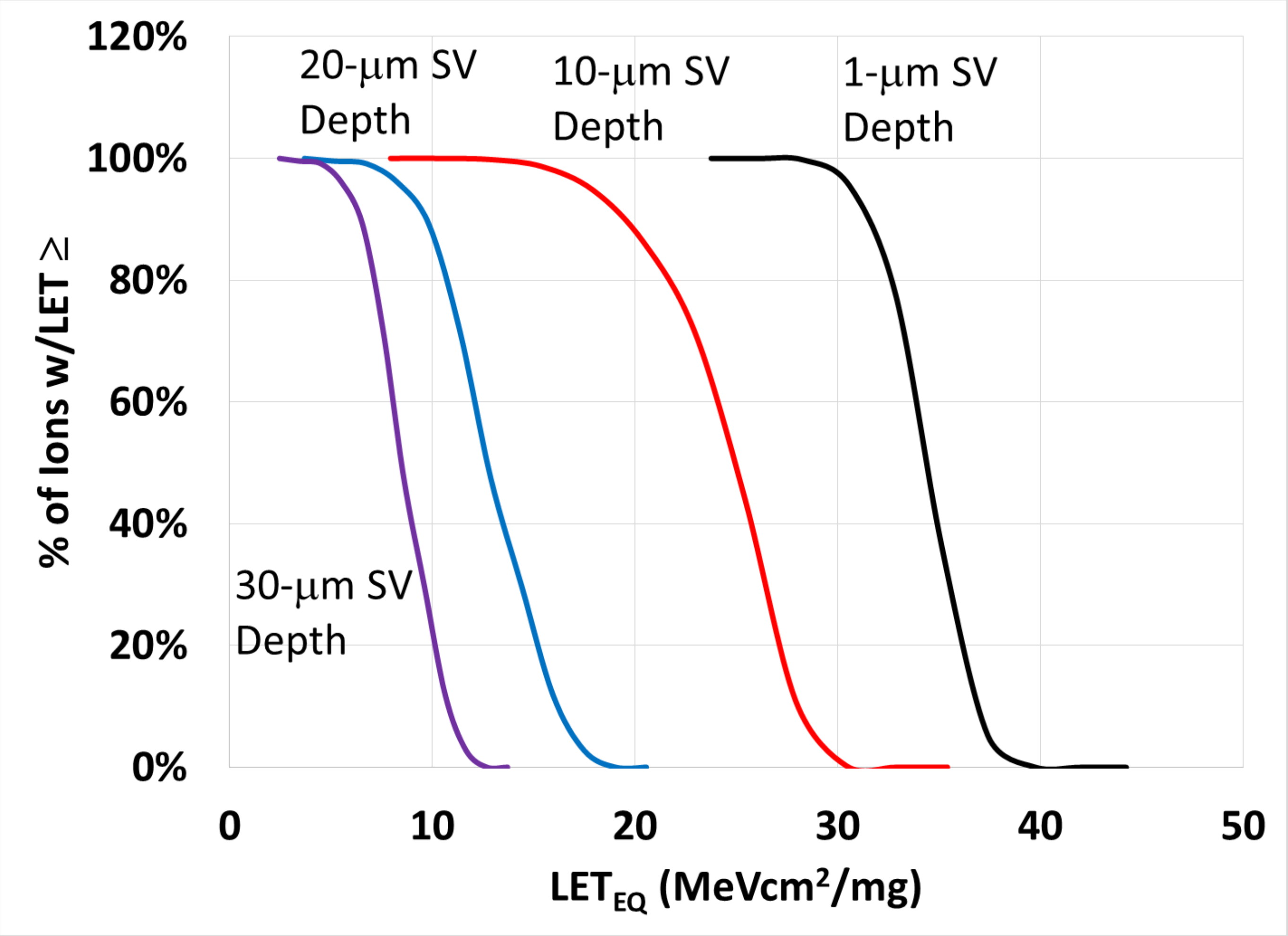
- Define Equivalent LET, LET_{EQ}:

$$LET_{EQ} = {E_{dep}}\Big/{(\rho \times d)} \quad ,$$

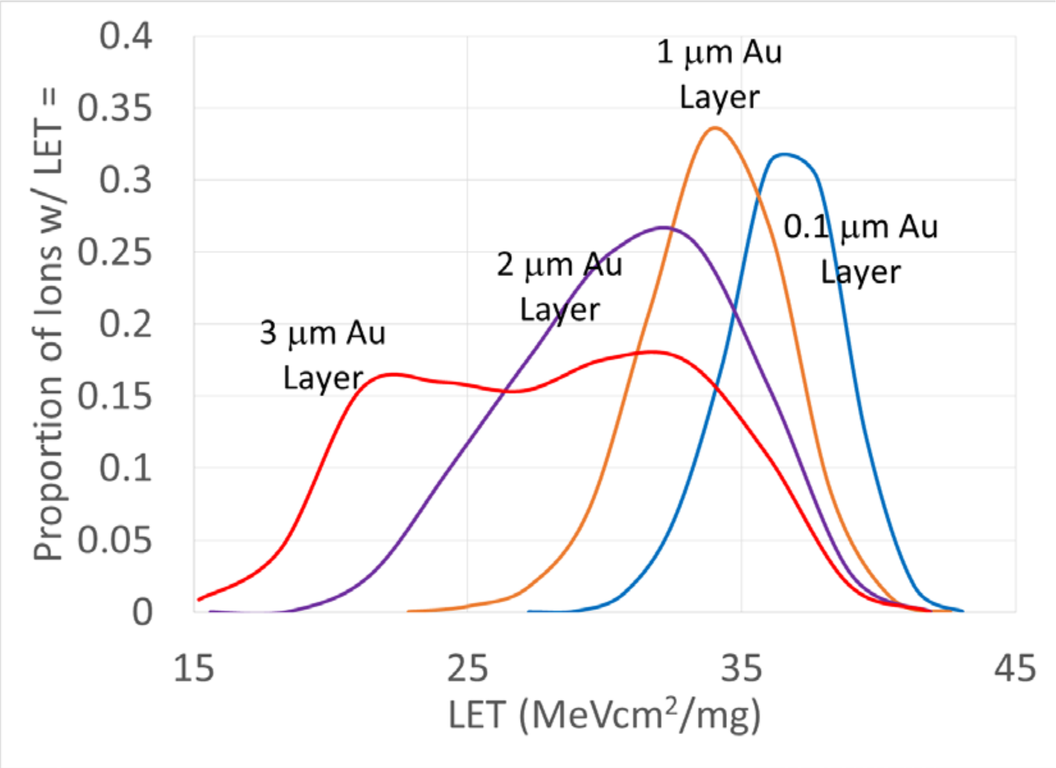
ρ=Si density, d=SV depth

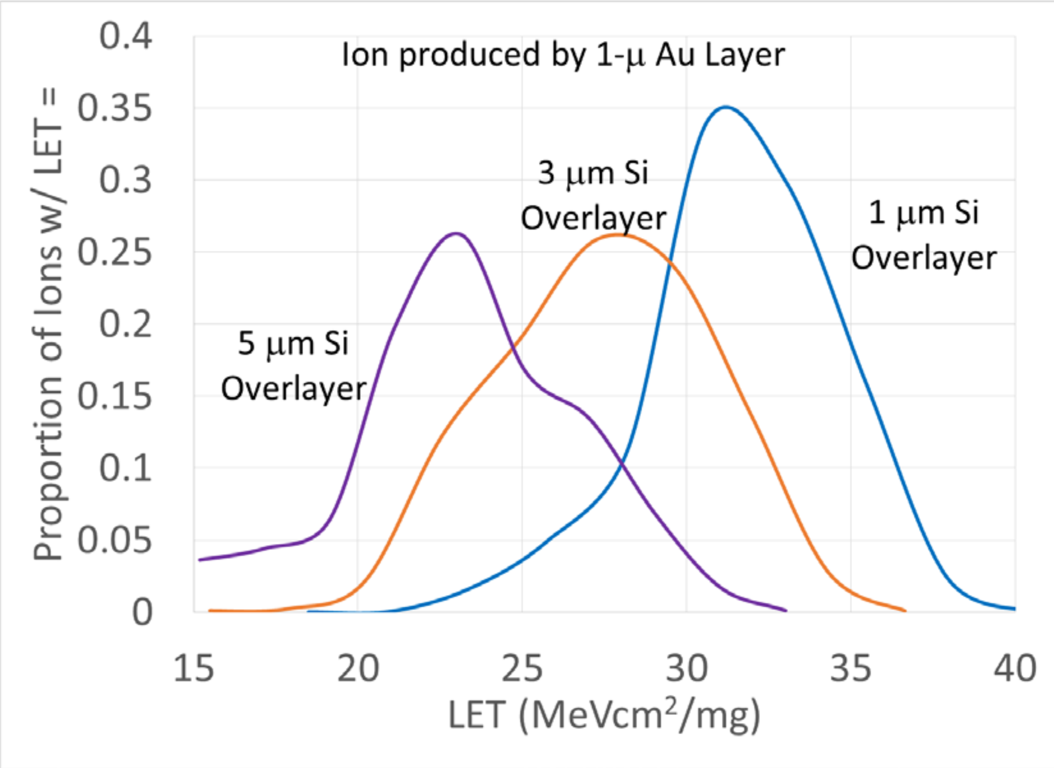
Look at Fluence vs. LET_{EQ}

- LET_{EQ} better captures physics than LET
  - More realistic picture of DSEE threat
  - Makes it easier to compare threat to environments where ion energy deposition is not range limited.
- Figure at right shows decrease of LET_{EQ} as SV depth increases.
  - E_{dep} = energy deposited in SV depth less than range of ion
  - E_{dep} = total ion energy if SV depth greater than ion range
    - Represents worst case.
  - SV for SEL, SEB and SEGR often >30 µm
- SV for dielectric rupture in ADI op amps thought to be shallow—worst case.



Transport through Materials Also Degrades LET Spectrum





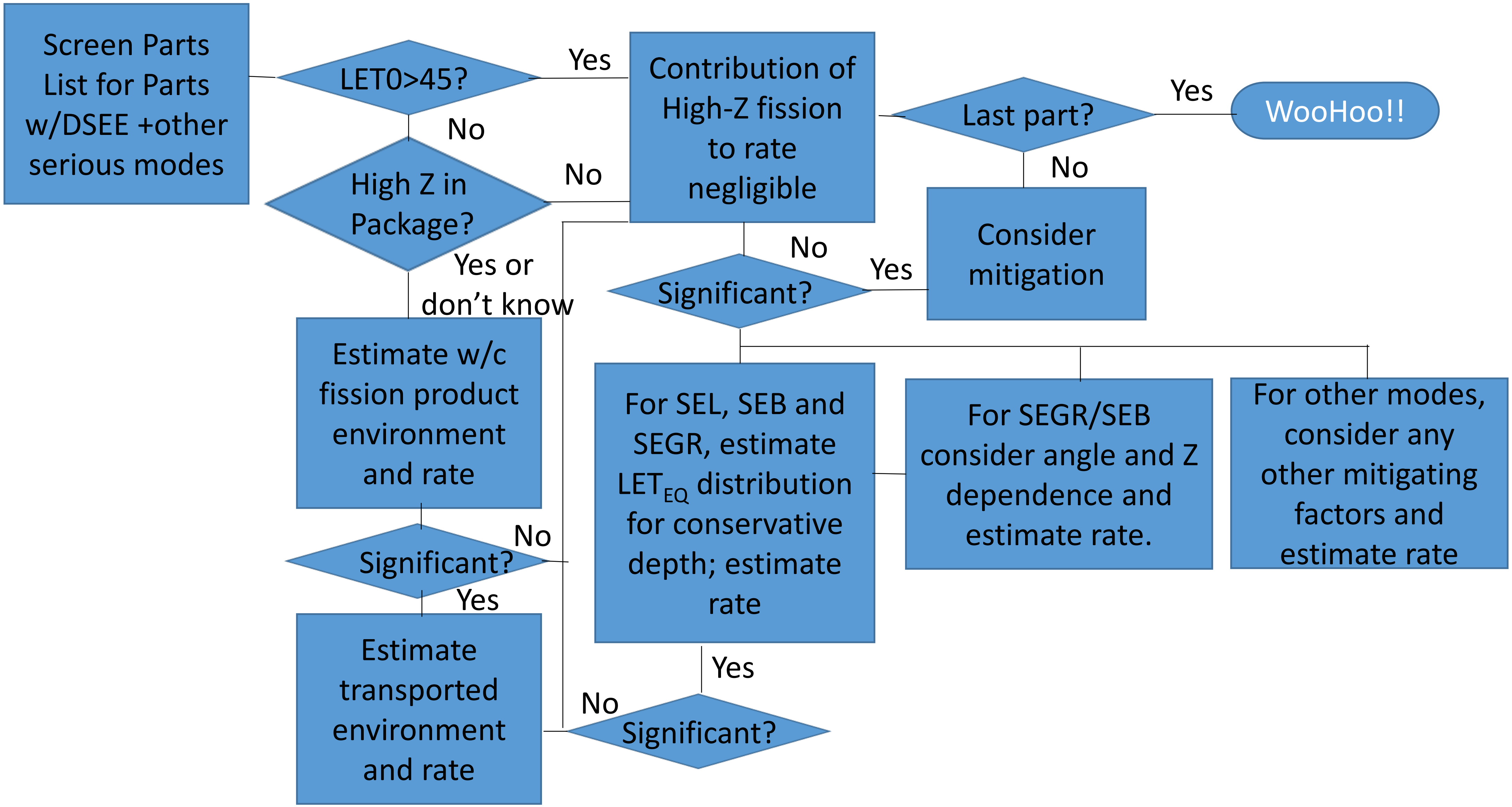
- Each additional μm of Au produces more ions bud also degrades ions already produced.
- WC fission product range in Au is ~6.5 μm

- Overburden on top of SV also degrades LET spectrum
- May include passivation, oxides, metal, etc
- Thicknesses here are in Si equivalent

Process Does Not Create New Failure Modes in Space

- Space Radiation Environments Contain Ions w/ $1 \leq Z \leq 92$
- Au fission events merely increase flux of ions w/ $30 \leq Z \leq 50$ and $20 \leq LET \leq 45$
- For this threat, look for parts susceptible to serious errors w/ onset LET>20
  - Nondestructive SEE, such as SEFI, MBU, stuck bits…
  - Destructive SEE, such as SEL, SEB, SEGR
    - For SEL, SV often>>10 μm, so ions are range limited
      - $\therefore$ Analyze in terms of LET_{EQ}
    - For SEGR, often have significant overburden on top of SV, ion Z, E, LET and angle of incidence are important
      - $\therefore$ Use transported Environment and analyze in terms of LET_{EQ}
    - Analysis for SEB is similar to SEGR
    - Mechanisms for other failures (SEDR, Schottky diode failures, etc.) may not be fully understood—use worst-case appropriate (e.g. taking into account transported environment, angular dependence if known, etc.)
- Dielectric failures of ADI op amps are probably a worst case
  - Onset LET ~20 MeVcm^2/mg
  - SV depth is shallow
  - Use energy dependence of cross section, transported environment, angular dependence (WC at normal incidence)

Process for Addressing Risk



Conclusions

- Proton-induced fission of high-Z materials can generate large fluxes of high-LET, high-Z ions
- Can dominate the SEE rate for some SEE failures in fairly proton-rich environments
- However, fission daughter products have low energy per nucleon
  - For Au fission products, range < 17 μm in Si; <6.5 μm
  - All fission product ions are on the low-energy side of the Bragg Peak
- In assessing risk due to high-Z materials in parts and packaging consider that
  - This mechanism cannot generate new failure/error modes; it only increases rate of pre-existing ones
    - If Onset LET for failure > 45 MeVcm^2/mg, this mechanism will not contribute; >40 then contribution negligible
    - Lower limit if concern depends on environment; for GEO, likely negligible if LET0<15; for ISS, if LET0<8 MeVcm^2/mg
  - Using actual energy dependence of σ(p + Au$\rightarrow$fission) significantly reduces ion flux
  - Short fission ion range means that ion LET degraded by passing through high-Z material + any overburden
    - More high-Z material means more ions, but most additional ions will have 20<LET<30, rather than 30<LET<40
  - Short fission ion range coupled with deep sensitive volumes typical of SEL, SEB and SEGR mean these threats pose less risk than that for the ADI capacitor failures or other modes with shallow SV
  - Angular dependence of SEB, SEGR will also lower rate for these failure modes.
- Capacitor failures like those seen in ADI probably present a worst case for this issue